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The future of insular beaches: Insights from a past-to-future sediment budget approach

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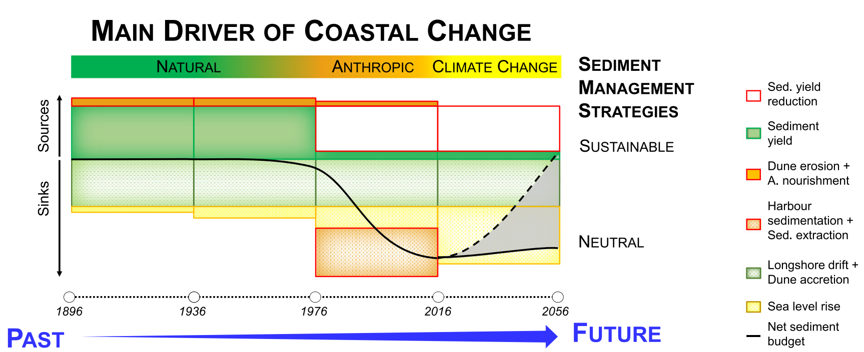
HIGHLIGHTS

- Long-term coastal evolution was explained by a past-to-future sediment-based approach.
- Onset of beach erosion was related to anthropogenic interferences on coastal system.
- Main drivers of coastal change will evolve from anthropic to climate-related.
- Preservation of beach environments depends on sound sediment management strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainable management of insular beaches, that are critical to tourism-based economies, depends on sound understanding of coastal evolution drivers. However, interconnections among geological, oceanographical, biological and human key-drivers of coastal change, operating at relevant spatial and temporal scales, remains poorly understood. This work aims at understanding and quantifying the main drivers of insular beaches evolution using a past-to-future sediment budget approach, and to address future coastal impacts raised by anthropogenic interventions and climate change. This approach was developed in Porto Santo's beach from the early 20th century to the middle 21st century.

Results show that anthropic activities undertaken during the late 20th century perturbed the existing long-term (natural) coastal stability. They caused significant reduction of the main sediment source (river sediment yield) and increased sediment sinks (e.g. sediment extraction from beach, harbour sedimentation). Altogether, this resulted in the onset of an erosive trend that persists until present. Projecting patterns of coastal change into the forthcoming decades strongly depends on sediment management strategies. We show that the adoption of a neutral strategy (i.e. compensating for anthropogenic-induced losses with beach nourishment) will not be enough to cease beach erosion, given the negative impacts related to acceleration of future sea level rise. Still, maintenance of the socioeconomic values of Porto Santo's beach can be achieved by triggering positive anthropic influences on its sediment budget. The past-to-future sediment budget approach proposed herein provided a unified perspective on the evolution of the main drivers of coastal change and simultaneously offers foundations for adaptations strategies aiming at increasing sustainability of insular beaches.

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1. Introduction

Sand beaches are known as extremely important features all over the world and can be considered a key element of sun- and sand-based tourism. Many small islands are tourism-based economies and are therefore strongly dependent on the quality of the beach environment (c.f. Palazón et al., 2018), which in turn depends on the supply and maintenance of the sand resource. For instance, around 50% of Canary Islands Gross Domestic Product (GDP) is related to tourism (May et al., 2003) while at Cabo Verde this figure is about 40% (WTTC, 2015). Tourism generates 25% of the Madeira region wealth in terms of GDP and provides more than 15% of the total jobs (CCIM, 2015; SRETC, 2017). However, beach systems are particularly vulnerable to direct human interferences, as well as to changes in the patterns of oceanographic forcing, such as wave regime, including extreme events, and sea level, that respond to climate change (Briguglio et al., 2009; Bishop, 2012; Wong et al., 2014; Nicholls et al., 2007; Nurse et al., 2014).

It is consensual among the scientific community that climate change-induced coastal erosion will be intensified and that without adaptation measures and adequate management policies many insular beaches are likely to disappear or became unviable by the end of the 21st century (Nicholls et al., 2007; Vitousek et al., 2017; Brown et al., 2014; Hinkel et al., 2018).

Adaptation measures aiming at sustainable beach management require in-depth knowledge of the coastal system evolution through time (past-to-future) at temporal and spatial scales adequate to management agendas and purposes. However, the complexity of the coastal system challenges the ability of high resolution morphodynamic process-based models to reproduce or forecast timely and accurately meso- to macro-scale coastal evolution. In fact, the so-called *bottom-up* or *reductionist coastal area* models may not be best approaches to simulate mesoscale coastal morphodynamics (de Vriend et al., 1993; Murray, 2013; Van Maanen et al., 2016). In contrast, the so-called *reduced complexity* (RC) models focus on simplicity (Paola and Leeder, 2011) and on the need to reduce the details incorporated in the models (de Vriend et al., 1993). RC models only consider the subset of processes that are essential to explain a phenomenon (e.g. Murray and Paola, 1994; Murray et al., 2009; Van Maanen et al., 2016; French et al., 2016a, 2016b; de Vriend et al., 1993; Cowell et al., 2003). They often take advantage of empirical models that capture the essential processes and trends of the coastal system at adequate time and spatial scales.

Sediment budget approach, based on the application of the sand continuity equation at the scale of a coastal cell (Komar, 1998), is a paradigmatic and effective example of RC models. Sediment budgets have been used to understand coastal evolution and to predict changes related to engineering works (e.g. Chapman, 1981; Rosatti, 2005; Bryan et al., 2008) but have seldom been used to forecast decadal to century scale impacts of climate change in beach systems.

The main objective of this study is to investigate the potential of a past-to-future sediment budget approach to predict future impacts on insular sand beaches raised by anthropogenic and climate-related changes. This innovative approach accounts for the entire beach-related sediment cycle, from source to sink. It respects the spatial interconnections among coastal, terrestrial and marine systems and considers the physical, chemical, biological and human drivers of coastal change.

The past-to-future sediment budget approach was developed and tested in Porto Santo, a small volcanic island in the North Atlantic. Porto Santo's economy, as many other islands in the Atlantic and elsewhere, depends on the quality of sandy embayed beaches with limited sand supply (c.f. Houston, 2008; Alexandrakis et al., 2015; Palazón et al., 2018). Guidelines for Madeira's tourism strategy recommended by both the region's Chamber of Commerce and Government, are convergent in indicating its sand beach as central for driving sustainable environmental, social and economic development over the period 2015–2021 (CCIM, 2015; SRETC, 2017). Porto Santo's beach can be regarded as an ideal study site for this investigation because it experienced typical management conflicts related to the development of a tourism-based island economy. Moreover, it is a relatively simple system, corresponding to a single coastal sediment cell, for which a relatively large amount of data is available. The beach rests upon a low-intertidal to sub-tidal rock platform for most of its extension and the magnitude of sediment storage, as well as sediment transfers are small, as shown below. The source-to-sink sediment budget approach presented here can be applied to any insular beach system, provided that all sediment budget components are adequately assessed. Overall, and regardless the case-study specificities, our approach is a relevant and novel framework for understanding the main drivers of coastal change, with obvious implications in development of coastal management strategies.

2. Regional settings

2.1. Geology and geomorphology

Porto Santo is a volcanic island that together with Madeira, Desertas and Selvagens, makes the Madeira archipelago, located about 900 km southwest of mainland Portugal in the North Atlantic between 30° and 33° N, and 15° and 17° W, (Fig. 1A and B). Porto Santo is roughly trapezoidal in plan shape (Fig. 1C) with about 14 km length and 8 km width and extending over 42 km^2.

This island is mostly composed of basic to medium-acid igneous rocks related to volcanic activity that ended about 8 Ma (Mata et al., 2013). In the Pleistocene and early Holocene, the island surface was blanketed by large expansions of wind-blown carbonate sand sourced from the island's shelf during lower than present sea-level stands. Wind-blown sand deposits consolidated to form aeolianites that fossilized earlier erosional surfaces (Soares, 1973; Ferreira and Neiva, 1996) nowadays are subjected to weathering and erosion. At present, aeolianites cover about one third of the island total surface and are more represented in the central-western part of the island (Fig. 2), their thickness reaching up to 50 m at Fonte da Areia (Soares, 1973). Aeolianites consist of medium and fine, well sorted biogenic sand. Sand grains are essentially made of calcareous algae fragments, broken bivalve shells and foraminifera tests, added by about 5% volcanic particles (Soares, 1973; Carvalho and Brandão, 1991; Silva, 2002).

Modern deposits include alluvial sediment in streams and rivulets, and beach-dune materials. Stream sediment consists of very poorly sorted gravel and gravelly sand, but where drainage basins collect sediment from aeolianites the sand contents significantly increases. Beach and dune sediments along the southern coast of Porto Santo are dominated by well to moderately sorted medium and fine sand, with texture and composition similar to the aeolianites (Pureza, 1961; Moura, 1961; Soares, 1973; Andrade et al., 2008). Other small pocket-beaches in the east coast, and east of the harbour (at the eastern end of the southern coast) are made of basalt (*s.l.*) cobbles and boulders, occasionally covered by a thin veneer of carbonate-rich beach sand.

Relief distributes unevenly across the island, with maximum altitude of 512 m at Pico do Facho. Volcanic ranges occur preferably at the eastern and western tips of the island and around the northwest coast. Peak alignments define a major drainage divide, separating a wide watershed system draining to the southern embayed coast, from smaller and narrow watersheds that drain to the remnant coastline (Fig. 2).

Porto Santo is margined by several islets. The islets of Ilhéu de Baixo (also known as Ilhéu da Cal) at the southwest, and Ilhéu de Cima at the east of Porto Santo beach (Figs. 1 and 2) are located very close to the shore and separated from the island by narrow and shallow channels.

The coast is mostly crenulated in plan shape, with abrupt cliffs and plunging cliffs and rare pocket-beaches, with exception of the southern coast. Most of the 9 km-long southern coastline is smooth and sandy and corresponds to an arcuate embayment. The construction of the Porto Santo harbour (between 1978 and 1984) near the eastern end of the bay, divided this coastal stretch into two separated beaches:

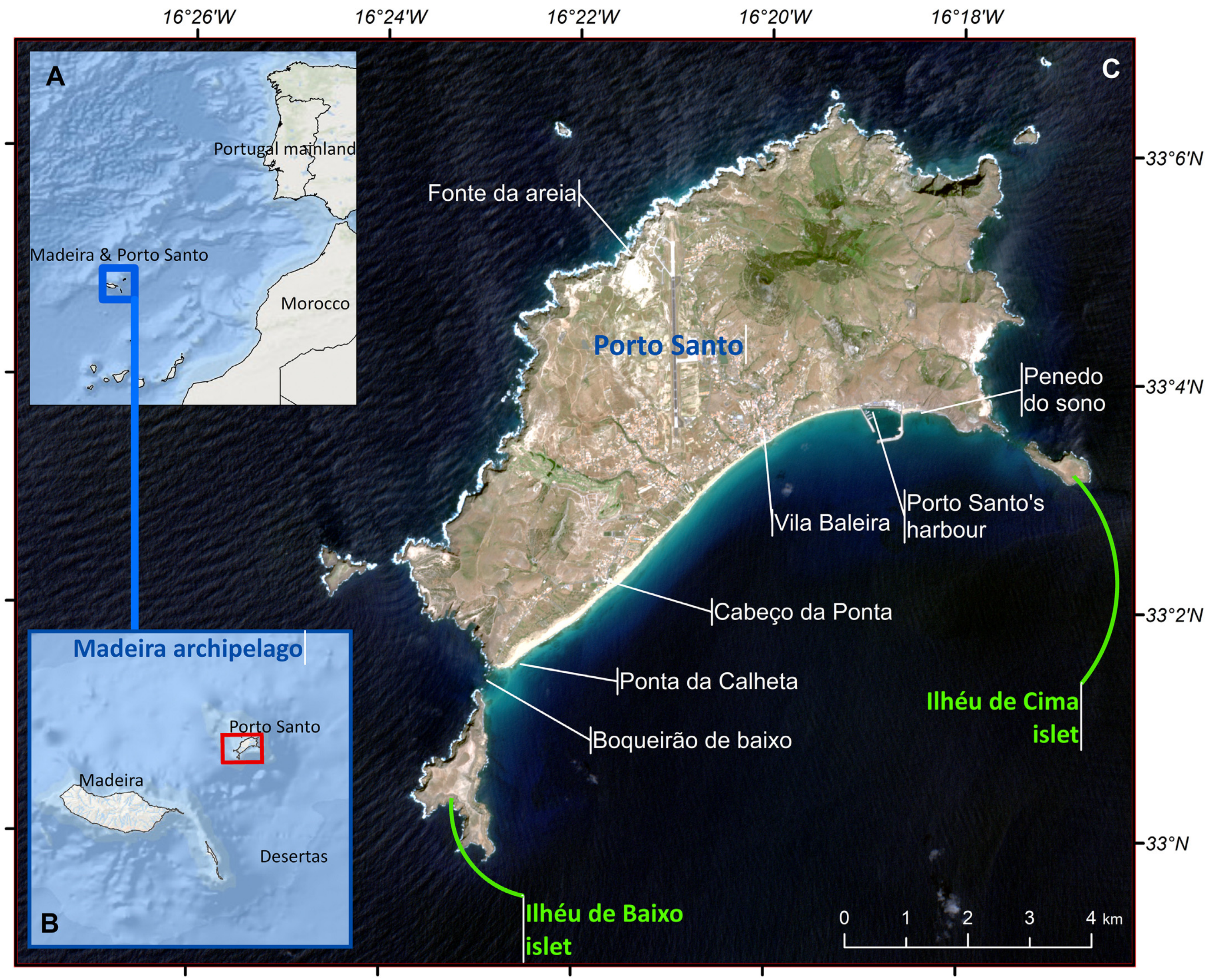

Fig. 1. A and B: Location of Madeira archipelago and Porto Santo island in the Atlantic Ocean. C – Porto Santo island and islets. (Basemap imagery source: Esri Ocean basemap and Sentinel-2 - 11-04-2017.)

Porto Santo beach, a continuous 7 km-long essentially sandy beach and Praia do Penedo beach, a 600 m-long essentially cobble beach. Alongshore differences in beach sediment existed well before the construction of port facilities.

Porto Santo beach is an intermediate-reflective beach mostly backed by a foredune ridge. At its westernmost tip (Ponta da Calheta) dunes are replaced by low cliffs, whereas to the East the beach is backed by artificial structures (Fig. 3). The beach profile usually includes a single narrow berm and a beach face. The beach accumulated over a gently seaward sloping rocky platform that develops at shallow depths in both the SW and NE extremities of the bay and is deeper along the central beach section. Therefore, the beach face toe extends seaward into a low tide sandy terrace at the central section, and through a low-intertidal to sub-tidal rocky platform at both ends.

The northern and southern shelf of Porto Santo is asymmetric in width, the former being much wider (Fig. 2). The shelf edge develops at depths ranging between 35 and 100 m and the shelf surface is in general smooth, with occasional reliefs where magmatic materials or aeolianites emerge from bottom sediment (IH, 2008). Shelf sediment is mostly unconsolidated biogenic carbonate sand covering an erosion surface carved into the volcanic substrate (IH, 2008).

2.2. Socio-economy

Human interplay with Nature started early in the 15th century just after arrival of the first Portuguese settlers. This is well illustrated in the description by Frutuoso (1586–1590) of the capital settlement (Vila Baleira, at present) having to be erected at a considerable distance (one cross-bow shot [circa 300 m] landward from the shore due to intense sand transport by wind ("*…não estão as casas perto do mar por causa da areia, que as atupira logo, mas haverá do mar às primeiras um tiro de besta …*") (sic, Frutuoso, 1586–1590. Conversely, human-influence on evolution of the Porto Santo coastline and hinterland landscape also started with arrival of settlers (see Frutuoso, 1586–1590; Carvalho et al., 2013; Gil, 2015 and references therein). Up to the early 20th century the coast was nearly depopulated with exception of people required to maintain rudimentary infrastructures, offering support to subsistence of maritime activities (small-scale fishery and boats). The sandy flatland extending landward of the foredune was occupied for agriculture that took advantage of a shallow water table, made accessible by digging shallow wells, and sheltering from offshore winds by the foredune ridge. Further inland, and despite water scarcity, agriculture, grazing and wood production, namely from wild olive trees (*Olea*

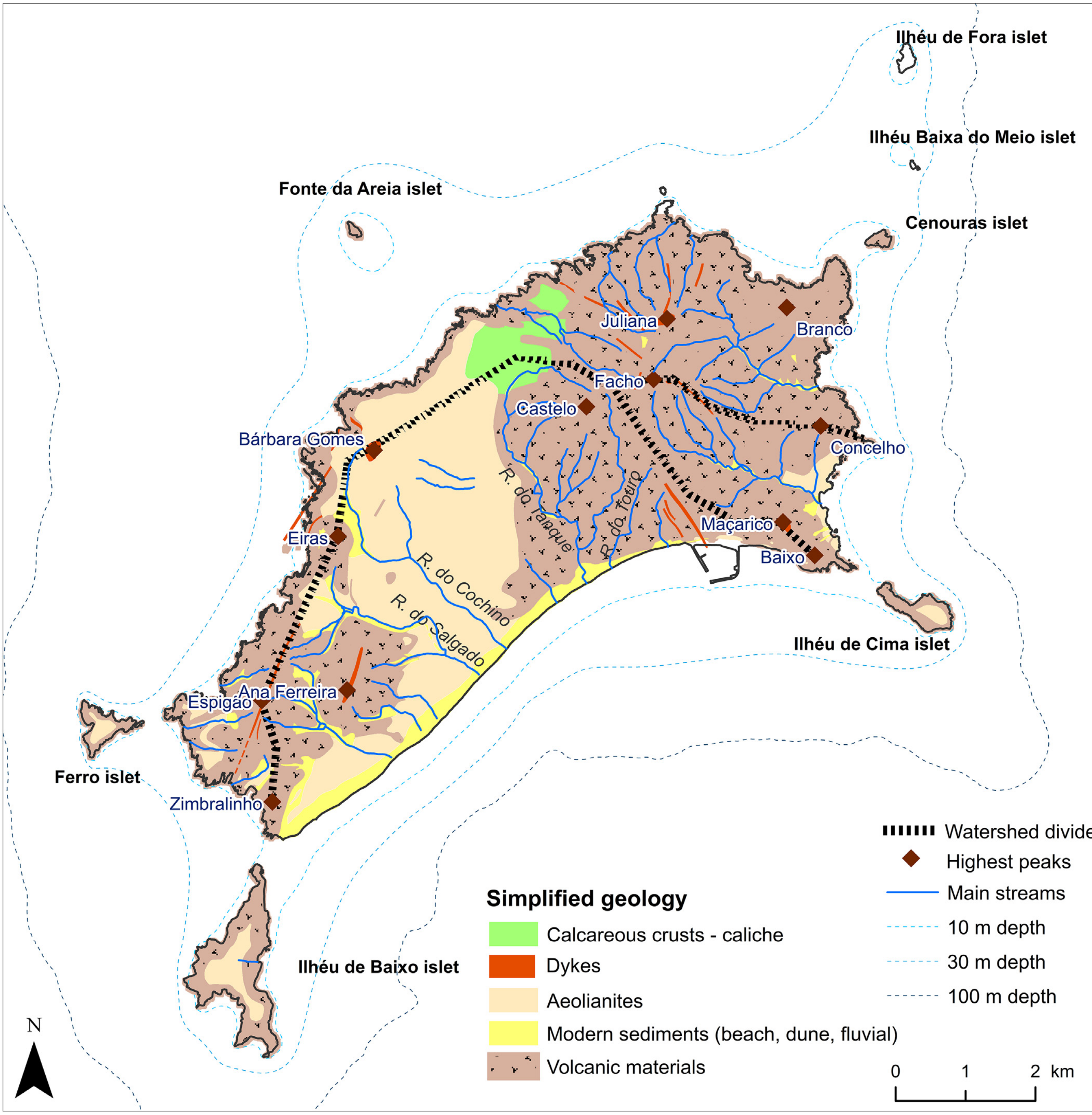

Fig. 2. Simplified geology and water courses at Porto Santo island.
(Geology simplified from LNEG MapServer, 2018.)

maderensis), juniper (*Juniperus turbinate)* and dragon-trees (*Dracaena draco*) steadily reduced the sparse and poorly diverse original flora cover to small and scattered patches.

The middle 20th century brought a dramatic change to the coastal landscape in relation to a shift towards a tourism-based economy, based on the attractive "golden" sand beach and mild climate. This change led to increasing urban, infrastructural and tourism development of the coastal fringe, together with higher water demand. The construction near the coastline was based on "hard" coastal development strategies, scarcely compatible with the natural dynamics and mobility of coastal features. This increased the risks impending upon people and assets located near the sea, while at the same time decreased the environmental value of the beach.

2.3. Climate

Porto Santo is located within the Sahel arid belt and features a semi-arid climate with annual average temperature of 18 °C and small thermal amplitude throughout the year. Given its small surface and low altitude annual precipitation is low, up to 400 mm. The island does not have permanent rivers, most of the surface being dissected by a dense network of active gullies. Rainfall episodes are concentrated in time;

Fig. 3. Oblique photographs of Porto Santo beach.
(Bottom right image - photographs position and perspective; photographs taken in 2010.)

hence the streams are ephemeral and only flow after heavy, occasional showers (Ferreira and Cunha, 1984; Andrade et al., 2008).

Wind is predominant from the north quadrant (64%) with average speed of about 20 km·hr^{-1}. Southern winds are unusual (about 5% of occurrences) and milder, averaging 15 km·hr^{-1} (Andrade et al., 2008).

Porto Santo coast is subjected to a mesotidal and semi-diurnal tidal regime. Mean spring tidal amplitude is 2.1 m (data from the 2001 Hydrographic chart 36401 published by Instituto Hidrográfico). Deep water wave regime offshore the northern coast is characterized by mean annual significant wave height and peak period of 2.4 m, and 10.6 s, and average direction of peak period of 333° (≈NNW) (the wave regime characterization can be seen in the Supplementary material - 3 Wave regime and depth of closure). In contrast, both the nearshore and coastal sections facing S and SE are sheltered from the prevailing northerly waves. This effect, added by refraction and diffraction of waves at islets channels, control the direction, power and energy density of waves propagating towards the southern coast that eventually reach Porto Santo's beach with significantly lower energy levels (Andrade et al., 2017; Supplementary material - 3 Wave regime and depth of closure).

2.4. Sea level

Local sea level variations are driven by eustatic, isostatic and tectonic changes. As in volcanic islands tectonic vertical movements may dominate sea level changes, the use of land-based sea level data is of major importance to decouple land movements from the eustatic sea level signal.

2.4.1. Local and global sea level

Historic records of sea level available for the study area are from the port of Funchal (Madeira Island) and date back to 1963 (accessed from National Oceanography Centre through the Permanent Service for Mean Sea Level – PSMSL; http://www.psmsl.org). This record includes data from two distinct tide-gauges, the first operating from 1963 to 2008 and the second from 2003 onwards. Large data gaps and anomalous values were detected in the period between May 1963 and October 1976, hence those records were not considered in the following analysis.

The general trend of sea-level change shows a relative sea-level rise (SLR) at an average rate of 2.5 mm·yr^{-1} between 1976 and 2009 and of 3.4 mm·yr^{-1} between 1976 and 2013 (Fig. 4). These values are in broad agreement with satellite observations of mean sea level offshore Porto Santo (+3.1 mm·yr^{-1}, for the period 1992–2018 - data retrieved from *https://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries.php* at 16.25° W, 33.25° N) and also with the +1.5 mm·yr^{-1}, long-term global mean SLR trend estimated by Church and White (2011) between 1880 and 2009. The match between local and global sea level rise in the late 20th and early 21st centuries suggests that local SLR is dominated by the eustatic component.

Sea level trends at Porto Santo were estimated in 0.9, 1.8 and 3.4 mm·yr^{-1}, for the periods 1896–1935, 1936–1975 and 1976–2013, respectively, indicating an increasing pattern compatible with acceleration. This time-series segmentation respects the periods considered in the following text, when addressing the sediment budget analysis (Section 3).

2.4.2. Future sea level scenarios

Considering the similarity between local and global sea level records, sea level scenarios at Porto Santo were based upon global projections until the end of the 21st century.

The Fifth Assessment (AR5) IPCC report projections range from 0.44 to 0.74 m rise in 2100, depending on the RCP (Representative Concentration Pathways scenarios – IPCC, 2013; Church et al., 2013) scenario adopted. More recently, the US National Oceanic and Atmospheric Administration (NOAA) updated scenarios for global SLR with the most up-to-date and scientifically supported results (NOAA, 2017), and presented a set of six scenarios recommended for coastal planning and risk management. These representative scenarios correspond to Global Mean Sea Level (GMSL) rise by 2100, of 0.3, 0.5, 1.0, 1.5, 2.0 and 2.5 m, respectively, in Low, Intermediate-Low, Intermediate, Intermediate-High, High and Extreme scenarios.

This study focuses on the development of adaptation measures aiming at beach sustainability at temporal and spatial scales adequate

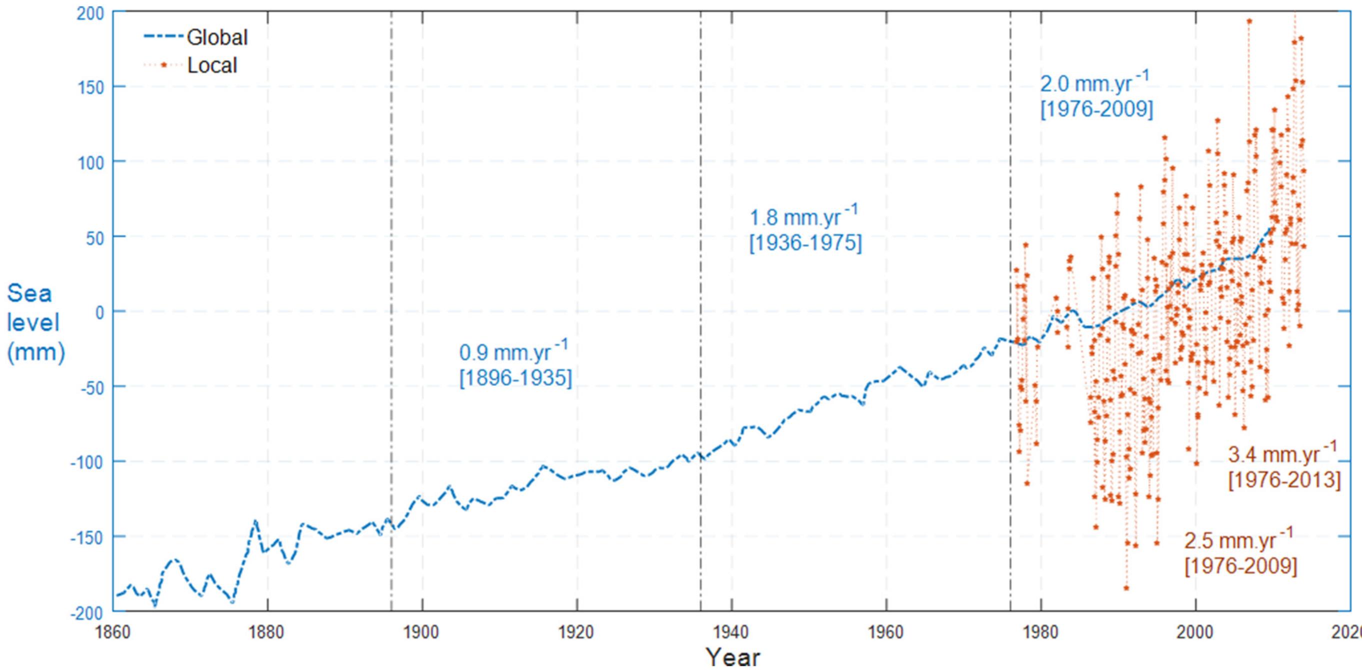

Fig. 4. Global average sea level from 1860 to 2009 (Church and White, 2011 – time-series as estimated from the coastal and island sea-level data) in blue; and Local - Funchal's - monthly mean sea level variation between 1976 and 2013 in orange. Mean SLR trends computed in different intervals are shown for both global and local records.

to management agendas. Thus, sea level projection considered a 40 year-long time-window (correspondent to the 2055 horizon) was based on NOAA's Intermediate scenario. Following this approach, a net rise of 0.36 m was considered for the period 2016–2055 which corresponds to an average SLR trend of 9 $\text{mm}\cdot\text{yr}^{-1}$.

3. Sediment budget analysis

The understanding of the main drivers of coastal change was based on the characterization of a comprehensive sediment budget, ranging from the recent past (1896) until the near future (2055) and balancing known sediment sources and sinks. Each budget component order of magnitude was calculated over four intervals of 40 years each, considering the relative importance of "natural" and anthropogenic constrains. In this work, solely the human activities with direct impact on the coastal sediment budget are classified as anthropogenic.

The first period, extending from 1896 to 1935, represents a sediment budget closer to pristineconditions. Here, the anthropogenic intervention is limited to agriculture activities over the coastal plain extending landward of the beach, and the beach was assumed to rest in equilibrium conditions.

The second period, from 1936 to 1975, represents a condition similar to the previous one in terms of human intervention, but incorporates unbalancing effects of a small acceleration of the SLR, that we relate with the onset of incipient coastline retreat.

The third period, from 1976 to 2015, represents the present-day condition, where the sediment budget is mostly driven by direct anthropogenic interference, with both the coastal system and hinterland surface following a pronounced shift in soil use and coastal development.

The fourth period, from 2016 to 2055, encompasses future scenarios. In this study we incorporated the views followed by governmental authorities and translated into policy guidelines and regulations aiming at minimizing human interference in the sediment budget and coastal zone.

Assessing Porto Santo beach sediment budget implied the evaluation of all components found to influence the sedimentary dynamics and sediment storage of the Porto Santo's beach littoral cell. The conceptual sediment budget can be described by both uni- and bi-directional dynamic connections between the hinterland, beach, foredune and inner shelf systems, materialised by sediment exchanges of variable magnitude in time and space (Fig. 5). Most significant components considered in this study are illustrated in Fig. 5 and listed below:

Sediment yield - effective sand supply to the beach sourced in watersheds by water erosion including sheet flow, streams and gullies;

Biogenic contribution - primary production of marine organisms, expressed by addition of mineral particles (essentially made of calcite and aragonite and produced by algae, foraminifera and molluscs) to coastal sediment;

Artificial nourishment – placement of sand in the coastal system in relation with dredging operations;

Harbour sedimentation – transference of sand by waves and currents from the coast into the harbour that is unable to be flushed out and returned to the coastal system by natural processes;

Sediment extraction – i) beach sand used for construction or stripped from the beach in the aftermath of the 1991 oil spill (see below); and ii) sand dredged for harbour construction and maintenance;

Sea level rise - sand lost to the inner shelf resulting from morphological readjustment of the beach-shelf system to higher than present sea level;

Dune accretion – sand lost from the beach to the foredune system by aeolian processes;

Dune erosion – storm-induced dune erosion;

Longshore drift – herein taken as a sink due to net longshore sediment loss to deep-water through Boqueirão de Baixo (Fig. 1C);

All afore-mentioned components were qualitatively and quantitatively evaluated in terms of order of its magnitude for each time-window considered.

3.1. Sediment yield

Clímaco et al. (2004) reviewed and expanded previous work on soil erosion intensity by Ferreira and Cunha (1984), and quantified the potential sediment yield to the beach related with both diffuse and concentrated surface run-off (in pristine conditions) in a maximum value

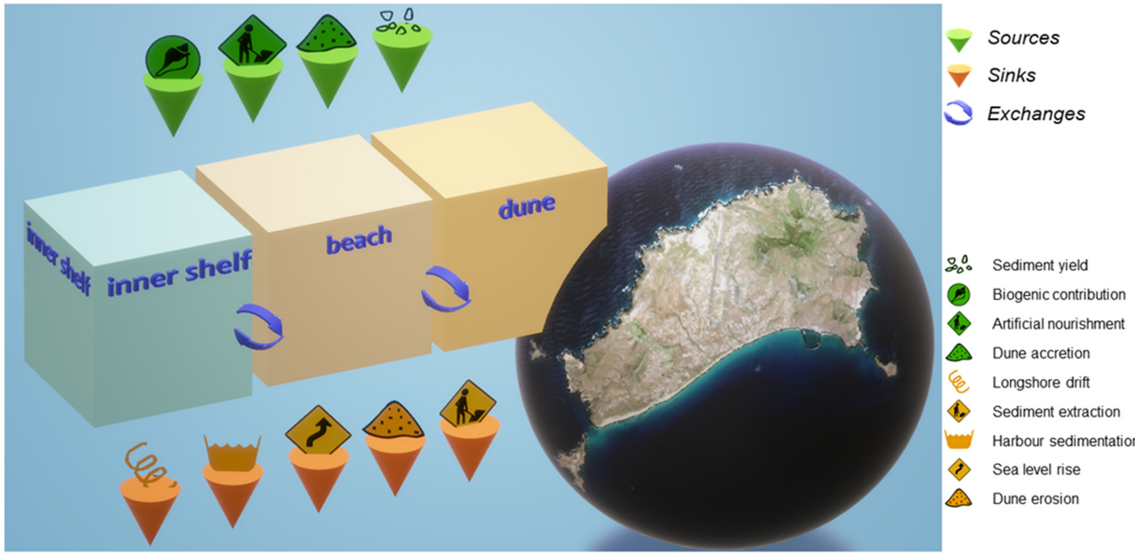

Fig. 5. Conceptual sediment budget framework, including all relevant sources and sinks.

of ca. 10,000 $m^3 \cdot yr^{-1}$. Andrade et al. (2008) investigated textural and compositional affinity and compatibility between the sand of Porto Santo beach and the sand in weathered source materials (considering regoliths, soil and stream sediment derived from both volcanic rocks and aeolianites) and concluded that aeolianites are the main sedimentary source of beach sediment (a detailed description of the textural compatibility between stream sediment and beach sand on Porto Santo is presented in Supplementary material – 2 Textural compatibility). Those results suggest that a 50% correction factor should be used to account for textural compatibility between beach and stream sand, indicating an effective sediment yield to the beach of about 5,000 $m^3 \cdot yr^{-1}$ (Supplementary material 2 – Textural compatibility).

Magnitude of the sand supply to the beach was strongly reduced since the 1970's by widespread construction of engineered infrastructures along the stream and gully networks, such as sedimentation ponds and weirs. These features, designed to control erosion and flow intensity, have disrupted the natural flow regime and incremented sediment retention upstream of the coastline (c.f. López et al., 2019, Lü et al., 2019). In consequence, the effective sediment yield to the beach system was reduced to about 15% of the magnitude in pre-engineering conditions (Clímaco et al., 2004).

In agreement with the data above, effective sediment yield related to soil erosion by water has been evaluated in 5,000 $m^3 \cdot yr^{-1}$ before the construction of flood control infrastructures and covering the 1896–1935 and 1936–1975 periods. Between 1976 and 2015 the magnitude of this source dropped to 750 $m^3 \cdot yr^{-1}$, according to the recognized proportion for effective sediment yield. Since no significant changes are expected to happen in the near future in both the drainage network and water retention systems of Porto Santo, the magnitude of sand input was considered invariant until 2055.

3.2. Biogenic contribution

The contribution of marine organisms to sediments of the Porto Santo's beach was investigated based on the compositional analyses of the biogenic contents of the beach sand, and its comparison with the inner shelf sedimentary cover (Andrade et al., 2008).

Biogenic grains of beach sand are predominantly fragmented calcareous algae (*Lithothamnion sp.*) followed in abundance by broken bivalve shells, foraminifera tests and other marine bioclasts. All organisms identified may have been sourced in the inner shelf or in aeolianite rocks outcropping at the coastline or further inland. Although biogenic content is relatively important in relation to beach sand composition, present-day primary production rates in the inner shelf are unknown. This makes it impossible to objectively quantify the present-day biogenic contribution to the sedimentary budget. However, semi-quantitative data on the aspect of bioclasts indicates that most of these particles bears a yellowish patina, a feature characteristic of aeolianite sand. The patina developed during phases of immobilization and exposure to subaerial weathering and soil forming processes. Preservation of the original colour in fragments of *Lithothamnion* and skeletal fragments of other marine organisms has only been occasionally observed. Altogether, these observations provide grounds to confidently suggest that the magnitude of this sedimentary source is (and has been over the last centuries) negligible.

3.3. Artificial nourishment and harbour sedimentation

Until present, no attempt to fill the beach using sediment taken from borrow areas in the shelf has been undertaken, and beach nourishment in Porto Santo has been strictly related to the disposal of sand dredged from the harbour. Data on location and volume of dredged sediment, as well as information on place of sediment disposal, were achieved combining information in reports from the Madeira port authority (APRAM - *Administração dos Portos da Região Autónoma da Madeira)*, with media news (including local and regional newspapers and TV), and interviews to the officer in charge of port operations, which accompanied harbour construction, dredging and beach-fill operations (Table 1).

The earliest dredging operation relates with Porto Santo harbour construction, first works having started in 1978. Dredging of the harbour basin and construction of the eastern curved jetty took place in 1984, and the western jetty was completed in 1986. This structure clearly influenced Porto Santo's beach sedimentary dynamics. The western jetty protects the harbour entrance from southwesterly waves and its head is founded 10 m below mean sea level (seaward of the seasonal depth of closure), thus creating a physical barrier to longshore sand transport (Clímaco et al., 2004). Seasonal sand transport by waves towards the easternmost section of the beach was blocked and the total length of the sand beach reduced to 7 km.

According to port authorities, the volume of sand dredged to create the harbour basin was mostly consumed in construction works. It broadly equals the volume of sand originally stored along the 750 m coastline front presently hosting port infrastructures. Thus, the emplacement of the harbour did not significantly impact the coastal sediment budget of the beach extending further westward.

Table 1
Summary of information about sand dredging, location of sediment disposal and date of dredging and beach-fill operations at Porto Santo.

Year	Objective	Volume ($\times 10^3$ m^3)	Use/deposition place	Source
1978–1986	Port construction	n.a.	Used for port construction	APRAM – official records
2004	Deepening of mooring facilities and navigation channels	112	Replenishment of Penedo do Sono cobble beach (eastward of port)	APRAM – official records
2008	Sediment removal from the small-boats marina	8	Beach stretch from Touro and Tanque's streams	TV Documentary (RTP Madeira), confirmed by head of port operations
2012	Experimental dredging of sand shoals at the harbour entrance	2	Santo da Serra and Palheiro's golf courses	APRAM – official records
2012	Dredging of the Travel lift deck area	5	Beach stretch from Touro and Tanque's streams	APRAM – personal communication from head of port operations
2014	Dredging of the Travel lift deck area	5	Beach stretch from Touro and Tanque's streams	APRAM – personal communication from head of port operations

Data in Table 1 indicates that harbour maintenance required a large dredging operation in 2004, involving removal of about 112,000 m^3 of sand from the harbour basin. These sediments were deposited along the berm and face of the originally cobble and boulder beach stretch located eastward of the port – Penedo do Sono beach, to increase its recreational and bathing values. Although no objective monitoring of this sand fill has been undertaken, qualitative observations based upon aerial imagery and photographs, together with eyewitness reports suggest that most of the sand remained in place until present, shifting between the lower and higher sections of the beach profile in tune with seasonal changes in wave regime. Minor losses may have existed, driven by cross-shore transport to the inner shelf or eastward drift across the northeastern channel (Boqueirão de Cima). Nevertheless, it is not plausible that this sediment was able to bypass the obstacle of harbour structures to the west and nourish Porto Santo's beach. Other dredging operations of smaller magnitude were performed in 2008, 2012 and 2014 (Table 1). Sand removed from the marina and travel lift areas in 2008, 2012 and 2014 was dumped on the berm of the ca 1 km-long beach section between the streams of Touro and Tanque (Fig. 2). On the other hand, sand dredged in 2012 from the sand shoals at the harbour entrance was used in golf courses, at that time under construction. While the former operations compensated losses related with sand retention in the harbour, the latter constituted a permanent loss to the beach system.

In synthesis, dredging operations and sand retention in the harbour strongly affected the beach sediment budget from 1975 onwards. Between 1976 and 2015, the total sink resulting from harbour infilling amounted to 132,000 m^3 (equivalent to a loss rate of 3,300 m$^3\cdot$yr^{-1}) while sand dredged from the harbour and used for beach nourishment summed only 18,000 m^3 (equivalent of a supply rate of 450 m$^3\cdot$yr^{-1}).

Based on ongoing Portuguese sediment management policies it is reasonable to assume that all sand obtained from future port dredging operations will be kept in the coastal system and used in full for beach nourishment. Dredging of the harbour must and will be repeated in the future for operational reasons, but return of this sand to the coastal system will cancel out the balance between source and sink, eliminating the negative impacts experienced in the recent past.

3.4. Sediment extraction

It is widely recognized by Porto Santo's inhabitants that sand and stone extraction from the coastal system was a regular procedure in the past (Fig. 6). In earlier times this practice was undertaken at artisanal and small-scale, without resorting to machinery, thus involving small amounts of sediment. Thus, the magnitude of this potential loss was disregarded in the sediment budgets over the first period considered in this study (1896–1935). However, the growth of construction works (harbour, roads and buildings) occurred in the 1980–90's, increased the demand for aggregates and raising sand mining to a non-negligible, though temporally restricted, sediment sink. In consequence, the beach-dune system was severely affected. Additionally, extensive cleaning of the beach took place in the aftermath of the 1991 "Aragon" tanker oil spill. This was achieved by sand stripping from contaminated areas of the beach and created a new, though temporarily restricted sediment loss to the coastal system. Clímaco et al. (2004) estimated the magnitude of losses associated to sand mining and beach cleaning in 20,000 m^3 and 30,000 m^3, respectively (cf. Clímaco et al., 2005). Both losses occurred in the 1976–2015 time-window, and correspond to annual rates of 500 and 750 m$^3\cdot$yr^{-1}, respectively.

3.5. Sea level rise

Prediction (and reconstruction) of shoreline changes due to a rise in sea level can be obtained using the equilibrium shoreface profile model (see, for example, Bruun, 1962; Dean, 1991; Dean and Dalrymple, 2002). According to this model, the magnitude of sediments expected to erode from the upper part of the beach/dune profile in response to SLR equals the amount of deposition in the lower section of the active profile, while the equilibrium shape of the entire profile remains invariant. In terms of sediment budget this is equivalent to consider a permanent sediment sink from the coastal system to the offshore that can be approximated using Bruun's rule (Bruun, 1962). This approach was considered along a 3 km-long beach stretch between Vila Baleira and Cabeço da Ponta (Fig. 1), where the whole active beach profile develops over sandy substrate. Depth of closure was determined following Hallermeier (1978, 1981) at 4.5 m below mean sea level, located broadly 200 m seaward from the coastline (the wave regime characterization and computation of the depth of closure is described in the Supplementary material - 3 Wave regime and depth of closure).

In coastal sectors where the submarine beach develops over a rocky platform, the sandy section of the profile terminates landward of the depth of closure. Thus, the assumptions underlying Bruun's rule are violated and the model no longer applies. In this case, which corresponds to more than half of the Porto Santo beach length and occurs at its western and eastern sections, the morphological readjustment model of Taborda and Ribeiro (2015) was used. This model relies on the assumptions of conservation of beach sand volume and beach profile shape, and considers that the beach berm elevation remains in equilibrium with mean sea level. Accordingly, the impact of the SLR on the position of the shoreline corresponds solely to retreat of the berm crest with reduction of supratidal beach surface, but sediment loss to the shelf is null or negligible.

The magnitude of this sink was computed considering the most appropriate rates of SLR for each period mentioned in Section 2.4 - Sea level. Results indicate magnitudes of sediment loss to the shelf in relation with SLR of 540 m$^3\cdot$yr^{-1}, 1,080 m$^3\cdot$yr^{-1}, 2,040 m$^3\cdot$yr^{-1} and 5,400 m$^3\cdot$yr^{-1}, in each time-window considered. Moreover, this loss

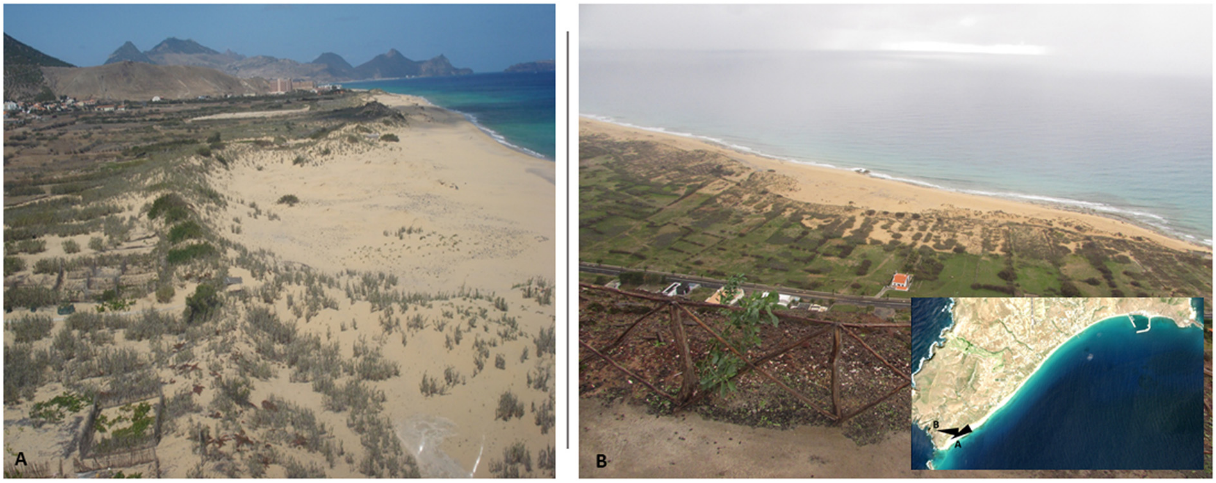

Fig. 6. Large blowout developed in relation with sand and stone extraction for construction at Porto Santo (inset - location of blowout in Porto Santo beach and viewpoints; photographs taken November 2016).

affects the central region of Porto Santo beach, with negligible contributions from both extremities.

3.6. Dune accretion and erosion

There are numerous field evidences indicating that foredunes margining the beach system have locally experienced accretion (Fig. 7). These evidences include sand-drowning of trees, fences or small boat houses originally located landward of the dune crest. However, with exception of blowouts that may advance landward from the dune crest for limited distances, there are no free-migrating forms, such as parabolic or transverse dunes, in Porto Santo. Accretion is noticeable in cases by increase of the apical height of the foredune and in most cases by inland migration of its lee slope.

Due to the lack of objective data on past dune morphology no objective quantification of the magnitude of sand transfer from the beach to the foredune system has been previously undertaken. Imagery analyses and interviews with local inhabitants and authorities are congruent in suggesting that aeolian processes acquired relevance as a sink to the beach system only from the third quarter of the 20th century onwards. This is explained by former intense and extensive agricultural occupation of the soil immediately landward of the foredune. Farming extended just to the landward foredune toe and used the lee slope of the dune to grow vineyards and these were carefully protected by wooden

Fig. 7. Field evidences of dune progradation and sand accumulation in the dune system, illustrating drowning of A – boathouse, B – fence and C - fig tree. (Bottom right panel - location of photos and viewpoints. Photographs taken in November 2016.)

fences. The top of the foredune and in cases its upwind slope were covered with *Tamarix sp* shrubs, to difficult sand bypassing, and excess of aeolian sand over agriculture soil was regularly shovelled back to the beach. Altogether, these practices constrained dune growth and landward expansion of foredunes.

Once the agricultural fields were abandoned, in the middle 1970's, the dunes were left to evolve naturally and aeolian processes have become a sediment sink. In agreement with these observations, we considered that sand transfer from the beach and subsequent retention in dunes had only impacted the sediment budget from 1976 onwards. Moreover, the estimation of volumes involved in this process considered only coastal stretches where a dune system exists today (summing 3,800 m, about half of the total length of the beach). Field surveys of the dune profile in sections bearing evidence of growth and enlargement allowed for quantification of morphological and volumetric changes. Field data suggest that inland progradation amounts to about 2 m on average and affects dune ridges with an average height of 4 m above the beach berm (Fig. 7).

Sand retention in dunes was therefore estimated in 30,400 m^3, for the 1976–2015 period, which is equivalent to an average rate of sand loss of 760 $m^3 \cdot yr^{-1}$. Climate change impacts on aeolian processes and related sand losses from the beach into dunes depend essentially on higher than average wind conditions. Despite difficulties to assess where and to which extent climate change will affect extreme winds, the study by Carvalho et al. (2017) suggests no significant changes in intensity and energy density over the broad Madeira region. In agreement the estimation above was assumed to remain invariant in the near future, and thus was applied in the time-window 2016–2055.

3.7. Longshore drift

Longshore sediment transport is of relatively small magnitude, in agreement with the low-energy wave regime and embayed shape of both the coastline and nearshore that is broadly similar (but not equal) to the curvature design of beaches in static equilibrium bays. Longshore drift, as computed by numerical modelling using the energy flux approach (see for example Clímaco et al., 2004, Andrade et al., 2008, Andrade et al., 2017) displays magnitudes and directions that vary in time and space along the bay. Few studies attempted to estimate the magnitude of the yearly net longshore drift at Porto Santo and the absence of objective measurements made validation of modelled results a difficult task. Notwithstanding this difficulty, (Andrade et al., 2008) and Andrade et al. (2017) suggested a net westward longshore drift of about 10,000 $m^3 \cdot yr^{-1}$. Both the direction and magnitude indicated above are in agreement with results in the study of Clímaco et al. (2004) that postulated the existence of a sand loss of 13,000 $m^3 \cdot yr^{-1}$ at Boqueirão de Baixo driven by longshore drift and crossing the western boundary of the sedimentary cell. The difference between both estimates is small and acceptable in the context of the uncertainty characterizing longshore drift computations. In this model, the southwestern tip of the bay is considered a gated boundary where losses in relation to a westward longshore drift are not compensated by an eastward longshore sand input. The northeast boundary of the beach cell, which prior to port construction corresponded to Boqueirão de Cima, has shifted its location to the western jetty of the harbour. Because this western port jetty is funded below the beach depth of closure (4.5 m) this limit is considered a closed boundary.

3.8. Coastal evolution

In a "natural" driven scenario, herein considered to have extended from 1896 to 1975, sand losses and sources related with sand extraction, dredging, aeolian processes, retention in harbour and beach fill operations were considered of negligible magnitude or did not exist at all. The variation of beach volume rested upon the balance between sediment yield (the only relevant sediment source) and sinks related to longshore drift losses through Boqueirão de Baixo, and losses related with SLR.

Knowledge of coastal evolution provides an independent solution to the beach sediment budget. Porto Santo's beach displays long-term stability of its plan shape. Moreover, previous studies on long-term coastal evolution could not unequivocally ascertain the existence of an erosive/accretional trend and there are no reports on coastal erosion effects until late in the 20th century. Altogether this concurs to hypothesize that until the third quarter of the 20th century the magnitude of sediment sources should have matched, at least approximately, the magnitude of sinks.

Taking into consideration the uncertainties associated with the evaluation of sediment yield and net longshore drift, it was considered that estimates of sediment yield were more accurate. This assumption leads to an estimate of slightly less than 5,000 $m^3 \cdot yr^{-1}$ for the average sediment volume loss driven by longshore processes through Boqueirão de Baixo. At present, there is very limited information on ocean wave behaviour in response to climate change. Notwithstanding, as the magnitude of the expected changes in wave parameters is small (and non-consensual in signal) (see for example Perez et al., 2015; Wang et al., 2014) we chose to consider the wave regime invariant in all time-windows. In agreement, the net longshore transport magnitude was also considered constant.

4. Integrated sediment budget

The integrated analysis of Porto Santo beach sediment budget components allowed to understand past beach evolution and provided valuable insights on order of magnitude of the processes that will condition its future evolution (Table 2).

4.1. 1896 to 1935

During this period the beach system remained in a dynamic equilibrium condition, sand losses having been matched by sources. The magnitude of sediments entering the beach (+5,000 $m^3 \cdot yr^{-1}$ through effective sediment yield) matched the total magnitude of sediments exiting Porto Santo's beach through Boqueirão de Baixo by longshore drift (−4,460 $m^3 \cdot yr^{-1}$) and lost to the shelf in relation with SLR (−540 $m^3 \cdot yr^{-1}$). All other components were considered subordinate and did not impact the sediment budget.

4.2. 1936 to 1975

From 1936 to 1975, GMSL rise increased relevance *per se* as a sediment loss and morphological adjustments of the beach started to occur. The magnitude of sediment loss in this 40-year period was estimated in −1,080 $m^3 \cdot yr^{-1}$, triggering a negative residual sediment budget, although of small magnitude (Table 2). The morphological expression of this deficit is one of coastline recession (erosion) but the magnitude of beach erosion and accretion driven by seasonality in wave regime exceeds by far the longer-term trend (Andrade et al., 2017 and Supplementary material 1 – Coastline evolution). The mean annual rate of the residue is −540 $m^3 \cdot yr^{-1}$, indicating that 21,000 m^3 of sand have been withdrawn from the system.

4.3. 1976 to 2015

Between 1976 and 2015, a major disequilibrium in sediment budget occurred with a huge increase in the magnitude of sediment losses, that peaked to −10,610 $m^3 \cdot yr^{-1}$. The increase is mainly related with the onset of novel sediment sinks such as sand extraction from the beach system (construction, beach cleaning), and sediment retention in harbour. Moreover, changes in land use practices (abandonment of coast farmland) eliminated the anthropic transferences of sand from the dune to the beach, therefore creating an aeolian-related net sink.

Table 2
Sediment budget of Porto Santo beach system in different time-windows, with indication of the main sediment sources and sinks, and gross contribution of natural, anthropogenic and climate change drivers. Values should be taken as order of magnitude estimates.

Components	Class	Equivalent annual rate (×1000 $m^3 \cdot yr^{-1}$)			
		1896–1935	1936–1975	1976–2015	2016–2055
Sediment yield [n]	Source	5	5	5	5
Biogenic contribution [n]	Source	0	0	0	0
Artificial nourishment [a]	Source	0	0	0.45	0
Dune erosion [a]	Source	0.76	0.76	0	0
Total sources		**5.76**	**5.76**	**5.45**	**5**
Stream sediment retention [a]	Sink	0	0	−4.25	−4.25
Longshore drift [n]	Sink	−4.46	−4.46	−4.46	−4.46
Sediment extraction [a]	Sink	0	0	−1.25	0
Harbour sedimentation [a]	Sink	0	0	−3.3	0
Sea level rise [cc]	Sink	−0.54	−1.08	−2.04	−5.4
Dune accretion [n]	Sink	−0.76	−0.76	−0.76	−0.76
Total sinks		**−5.76**	**−6.30**	**−16.06**	**−14.87**
		Equivalent annual rate (×1000 $m^3 \cdot yr^{-1}$)			
		1896–1935	1936–1975	1976–2015	2016–2055
Residual budget		**0**	**−0.54**	**−10.61**	**−9.86**
Natural – [n] (sum)		−0.22	−0.22	−0.22	−0.22
Anthropogenic – [a] (sum)		0.76	0.76	−8.35	−4.25
Climate Change – [cc] (sum)		−0.54	−1.08	−2.04	−5.4

Altogether, these changes explain about 80% of the sand deficit that prevailed over this time-window. Moreover, the rate of sand loss to the shelf, related to SLR, doubled in comparison with the previous period and nearly responds for the remaining 20% of the losses. Despite some of the materials dredged from the harbour having been returned to the beach system, the small magnitude of this man-induced source was clearly insufficient to counterbalance the overall losses. As a result, sediment sinks largely exceed the magnitude of sand input (that was reduced to about a quarter of its magnitude in "natural" conditions) leading to a twenty-fold increase of the sand deficit. This sediment unbalance translated in generalized coastal retreat.

In this period, the sediment budget was primarily influenced by human interventions. Anthropic action overwhelmed changes ascribable to "natural" causes, such as climate change-induced rise in sea level and associated losses to the shelf, despite the fourfold increase of this sink when compared with "pristine" conditions (Table 2). Altogether, these processes have contributed to the increase of coastal erosion and loss of aesthetic quality and comfort of some sections of the beach, as largely reported by newspapers and broadcasting media, also triggering pressure for remedial action from tourism stakeholders and the general public.

4.4. 2016 to 2055

Projections for the 2016–2055 period were built assuming a neutral sediment management strategy, as indicated by national and regional governmental policies and coastal management programmes in force. This implies that sand and pebble mining at the beach or dunes is no longer possible. On the other hand, all sediment that will be made available by harbour dredging (inevitable to maintain operations) will be used for beach nourishment. On the long-term this procedure cancels the sink-effects of dredging and retention in harbour with beach replenishment, regardless of the volumes involved. No objective plans of action have been so far established to manage dune evolution, thus this sediment sink was considered active in future scenarios. Sediment yield was considered invariant, regardless expected changes in average rainfall and mean temperature (cf. Santos et al., 2004; Cropper, 2013) as the dominance of anthropic influence over changes in natural processes was assumed to persist. Indeed, only the removal of flood-control structures could significantly change solid discharge to the beach. However as this would increase flooding effects and risk to unacceptable levels, maintenance of these structures, and consequently of the present-day stream discharge are reasonable assumptions.

The sediment budget projected for this period is negative with a net loss estimated in $-9{,}860\ m^3 \cdot yr^{-1}$, a rate that corresponds to a total volume of near 400,000 m^3 over forty years. This result is mainly related to the effects of the acceleration of SLR and resultant sediment loss to the shelf (Table 2). Sea level rise, solely, corresponds to a sediment removal of $-5{,}400\ m^3 \cdot yr^{-1}$ (about 250,000 m^3 of sand in 40 years), about 50% of the total sand deficit foreseen for Porto Santo beach. Results indicate that if no supplementary actions are taken, the erosive trend that characterizes the "present-day" situation (corresponding to the 1976–2015 time-window) will persist. Although no significant difference exists in the rate of coastal change determined for the 1976–2015 and foreseen for the 2016–2055 periods, the causes driving these changes are markedly different. Instead of man-induced (and clearly reversible) interventions, that prevailed in modulating the sediment budget throughout the last 40 years, the projected sediment budget will be essentially affected by SLR, with an increasing signature of cross-shore sediment transfers determined by climate change.

5. Drivers of coastal change

This study builds on a past-to-future comprehensive sediment budget approach, at the scale of a sedimentary cell. This approach follows recommendations of Nicholls (1998) for planning and management of coastal land and risk. Solving Porto Santo beach sediment budget enables an integrated perception of this beach system and behaviour through time, allowing for the pattern and magnitude of change to be deduced from the imbalance between sources and sinks. The study relies upon and integrates multiple types of data, including field observations and measurements, technical reports, media information, interviews with inhabitants and inedited information and data supplied by regional authorities.

Sediment budget reconstructions and projections (Table 2 and Fig. 8) are affected by uncertainties, including the ones inherent to the mapping of the coastline indicators, estimations of dune volumes, sea level data and projections, definition of future climate scenarios, assessment of effective sediment yield to the beach and reliability of nonformal and formal information (e.g. sand mining and beach stripping).

In this sense, values of sediment budget components should be regarded as order of magnitude estimates that should be revised as more data become available. Notwithstanding this recognizable

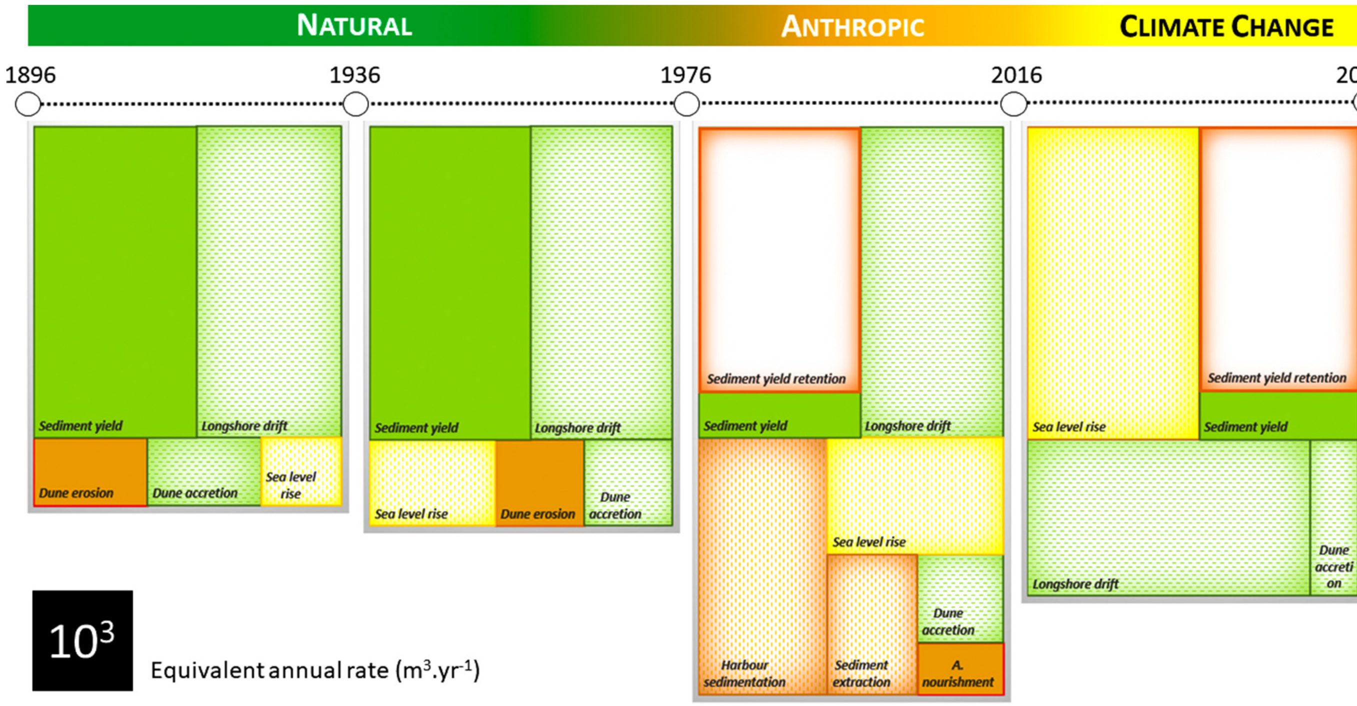

Fig. 8. Comprehensive sediment budget of Porto Santo's beach for the periods analysed, with indication of the contribution of Natural, Anthropogenic and Climate Change-driven processes (respectively in green, orange and yellow). Solid-filled patterns represent sources while dashed patterns represent sinks.

limitation, the match between the overall sediment budget and past coastal evolution, as well as the remarkable convergence between estimates presented herein and in previous studies, validates the time-integrated source-to-sink sediment budget approach, especially in what concerns qualitative to semi-quantitative assessment of the main drivers of both past and future coastal evolution.

Assessment of the sediment budget in different time-windows shows that the nature, and related weight of different components evolved in time. Data represented in Fig. 8 clearly reveals a shift in predominance of natural, anthropic and climate change-related processes as main drivers of coastal change.

Long-term stability of the beach system observed between 1896 and 1975, represents a condition of dynamic equilibrium that resulted from a close match between source and sink magnitudes, which was modulated by natural processes such as sediment yield and net longshore drift. During this period anthropic influence in coastal equilibrium was minimal. The onset of a small erosional trend after 1936, deduced from the sediment budget analysis (net loss around 500 $m^3 \cdot yr^{-1}$), can be related to the inception of acceleration of global sea level rise.

In contrast, in the recent past (1976 to 2015) direct anthropogenic interference peaked. Human-induced perturbations reduced sediment sources (sediment yield) and generated new sinks (sediment extraction and harbour sedimentation) (c.f. López et al., 2019, Lü et al., 2019). Simultaneously, the acceleration of sea level rise doubled the magnitude of the associated cross-shore sand losses. Altogether, these processes translated into unprecedented and significant beach erosion (net sediment loss of ≈11,000 $m^3 \cdot yr^{-1}$).

Sediment budget analysis shows that projecting patterns of coastal change into the future, until the mid-21st century (2056), strongly depends on global climate-change and socio-economic scenarios adopted. Sea level rise and sediment management strategies were considered herein as key-drivers of future sediment budgets. Considering an intermediate scenario for sea level rise over the forthcoming 40 years, as described above, sediment budget analysis indicates that the magnitude of cross-shore sand losses will significantly increase, more than doubling the present-day magnitude. Given that, even if direct anthropic negative interference is halted by means of adopting a neutral sediment management strategy (i.e. compensating anthropogenic-induced losses resorting to beach nourishment), the beach will remain in an unbalanced erosive state (Fig. 8 and Table 2), the magnitude of sinks largely surpassing the sources. Porto Santo's beach sustainability can only be achieved if the erosive trend (related to a net loss of ≈10,000 $m^3 \cdot yr^{-1}$) is cancelled or reversed. This may be achieved through a set of anthropogenic actions with positive impact on the sediment budget, such as increasing the magnitude of beach nourishment. Sustainability of Porto Santo's beach does therefore depend on adaptation strategies built upon sediment management options.

While before of the Porto Santo's construction peak, in the middle of 20th century, the main driver of coastal change was almost exclusively driven by natural processes, the period between the late 20th century and the early 21st century's is clearly marked by increased pressure and impacts of anthropic nature on the coastal zone. For the next decades, and further on, Porto Santo's beach evolution will depend mostly on climate change effects if no positive anthropic actions are applied.

A complementary, but equally relevant, key-issue for coastal management and decision taking in Porto Santo and insular beaches worldwide, is sand availability and sand management. Beach nourishment implies borrowing quality sand from external sources, such as the insular shelf and watersheds, and this sand is a limited resource. Thus, sediment-based strategies depend also on sustainability of the sand resource, that should be quantified and protected.

6. Conclusions

The past-to-future sediment budget approach developed in this study is a reduced-complexity method that provided an integrated overview of the processes that drives the evolution of an insular beach at temporal and spatial scales adequate to management agendas and purposes. The main difficulty inherent to this approach is the need of quantitative assessment of all relevant components influencing the

budget of beach sediment over time. This drawback can be overcome by considering multiple types of data and information (including non-formal and formal) on sediment budget components, and their combination, to constrain and reduce the uncertainty of quantitative estimates, which also should be matched against independent data, such as coastal evolution patterns.

Results obtained at Porto Santo's beach show that long-term coastal equilibrium was perturbed in the late 20th century in response to anthropic interventions affecting both the coastal and watershed systems. The human-related sedimentary deficit was the main responsible for the onset of generalized beach retreat and dune erosion, the negative impacts related to changes in sea-level having played a minor role. Regardless the considerable uncertainty characterizing projected sea level rise scenarios, we argue that elimination of the sediment sinks generated by direct human interference with the coastal system in the recent past will be insufficient to compensate for the magnitude of the sediment deficit, which will persist similar to the present-day. We show that implementation of a positive sediment budget strategy in insular beaches is the only way to achieve the objectives of stopping erosion and stabilizing the coastal system, and simultaneously maintaining or improving their socioeconomic and aesthetic values. In the forthcoming decades, sea level rise is expected to significantly amplify the beach erosive trend, so beach sustainability depends upon the adoption of sound adaptation measures centred on tenable sediment management strategies.

This sediment-centred framework enabled the recognition of both climate and non-climate- drivers of coastal change and provided solid foundations for adaptations strategies aiming at increasing sustainability of insular beaches. Given its nature and components, the approach used herein is readily applicable to embayed beaches with limited sediment supply and small sand volumes resting over shallow rock platforms in other volcanic islands (e.g. most of the Canaries, Hawaii, Cabo Verde, Santorini or Stromboli). Rather than being a deterministic tool to predict coastal changes, this framework, provides means to understand, quantitatively constrain and rank the main drivers of coastal change. In turn, this allows forecasting patterns of beach evolution in insular beaches worldwide.

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CRediT authorship contribution statement

Ana Nobre Silva: Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing - original draft, Writing - review & editing. **Rui Taborda:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing - original draft, Writing - review & editing. **César Andrade:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing - original draft, Writing - review & editing. **Mónica Ribeiro:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing - original draft, Writing - review & editing.

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